Recent Technological Advances in Flexible Electronics

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Abstract

Flexible electronics is a new field of research that is becoming popular day by day. The arrival of new era of foldable power sources in integration with electronics has led to growing demand for portable, flexible roll-up displays, biomedical sensors and wearable devices. Devices that are bendable or even wearable are unique in their functionality and convenience. Not only do they have excellent electrochemical performance but also there is a drastic reduction in the devices tendency to break or damage under pressure. We shall discuss about some of the latest technological innovations in foldable electronics like flexible solar cells and place special focus on cable-type flexible batteries. We shall also introduce various functional electrodes explored for flexible lithium ion batteries based on carbon nanotubes, graphene paper and also on a newly advanced technology of using inkjet printable ink based on graphene(or prepared from graphene) and flexible LEDs. A comprehensive discussion on supercapacitors and Proton Exchange Membrane Fuel Cells (PEMFCs) which are at the forefront of present day energy storage technologies is dealt within this paper. These devices are high in demand in the modern world and provide an avenue for extensive research to obtain superior next generation technologies.

Keywords: cable-type, carbon nanotubes, cable-type, graphene, inkjet printable ink, LEDs, PEMFCs, supercapacitors.
1. Introduction
In recent times, the new emerging trend of flexible energy storage systems in integration with electronic equipment’s has taken a rapid growth and have garnered to become the cynosure of all eyes. There has always been a strong interest in portable and flexible electronic equipment such as roll up displays and wearable devices. In order to achieve functionality of these devices in flexible form, compliant battery units with high energy and power density should be considered. The main purpose of this invention is to free the development of innovative energy storage systems from design limitation which is considered to be the most important technical pre-requisite. This paper includes discussion on recent progress made in the development of next generation flexible energy storage systems such as lithium-ion batteries, along with an overview of the progress made in supercapacitors and flexible proton exchange membrane fuel cells (PEMFCs).

In this paper, the present status and future development of each energy storage system such as lithium-ion batteries, supercapacitors and proton exchange membrane fuel cells is described based on nanostructured electro-active materials, shape conformable solid electrolytes and soft current collectors. A more focus has been dedicated to the technological advances in flexible lithium ion batteries and supercapacitors which have managed to gain maximum attraction and smartly expanded their application scope. The second half of the paper describes the development of a new design concept called cable type flexible lithium ion battery with Omni-directional flexibility that represents a considerable advancement in conventional battery design.

2. Flexible Energy Storage Systems
2.1 Flexible lithium ion batteries
The various functional electrodes explored for flexible lithium ion batteries are

2.1.1 Carbon Nanotube
Carbon nanotubes have unique electrical, optical, mechanical and thermal properties which make them very attractive for a wide range of applications. They have high electrical conductivity and electron mobility which has paved way for an extensive study for their possible use in diverse applications of flexible electronic devices. A structure of thin, flexible lithium-ion battery was developed using plain paper as a separator and free standing CNT thin films as current collectors. The current collectors and battery materials were integrated onto a single sheet of paper through a lamination process. The thin lithium-ion paper battery was very thin of approximately 300 micrometer thickness, had robust mechanical flexibility that could be bent up to a radius less than 6mm and a high energy density of approximately 108 mAh/g. Despite of their excellent performance, it was observed that direct coating of electrode slurry onto plain paper led to the occasional internal shorting of the device due to the leakage of the electrode material through a large sized hole in the paper. Therefore, an
addition, an additional lamination process was required to apply a thin layer of polyvinylidene fluoride onto the paper.

Another CNT based approach makes use of flexible and binder free electrodes of approximately 30 micrometer thickness comprising of interpenetrative nanocomposites of very long CNTs vanadium oxide (V$_2$O$_5$) nanowires. These electrodes exhibit excellent electrochemical performance due to their strong architecture that enables effective charge transportation and electrode integrity. The only challenge to this is the use lithium metal as a counter electrode.

2.1.2 Graphene paper
In a new approach to flexible energy storage systems, the use of flexible electrode based on free-standing graphene paper to be applied in lithium rechargeable batteries has been suggested. Graphene paper is a functional material which not only acts as conducting agent but also as a current collector. The properties of graphene are attractive and intriguing to engineers, in particular to designers and developers of next generation electronic devices. It has a unique combination of outstanding properties such as high mechanical strength, large surface area and high electrical conductivity which makes graphene paper a suitable base material for flexible energy storage devices. Graphene based flexible electrode can deliver significantly improved performances in electrochemical properties such as in energy density and power density and also has a better life cycle compared to non-flexible conventional electrode. This unique graphene paper of diameter 10 cm and thickness of 10 micrometer was prepared by mechanically pressing a graphene aerogel. A distinctive characteristic of the resulting graphene paper was that it allowed graphene sheet folding which could effectively enhance the accessibility of lithium ions and the electrolyte. Graphene when integrated with vanadium oxide electrode results in fabrication of thin, lightweight and flexible batteries. The cathode material V$_2$O$_5$ is grown on graphene paper by pulsed laser deposition (PLD – a well-known technique in fabricating thin films with its capacity to make high quality oxide ceramics with relatively fast deposition rates.) in a vacuum chamber at a base pressure less than $10^{-5}$ Torr. The target was prepared by cold pressing from a V$_2$O$_5$ power and sintering at 600$^\circ$C in air for 6 hour.

2.1.2.1 Inkjet printable ink based on graphene
Graphene is considered to be one of the most ideal materials suitable for flexible electronics due to its remarkable properties. Its unique properties have expanded its application in flexible electronics and have helped researchers to come up with a new advancement in it. A graphene based ink has been developed by scientists showing high conductivity and tolerance to bending. They used it to create inkjet print graphene patterns that could be used for extremely conductive electrodes. The resulting patterns were found highly conductive and could lead to low cost applications in flexible energy storage systems. Inkjet printing is one of the most sophisticated printing methods that is relatively inexpensive and highly scalable. It has been previously...
explored as a method for fabricating transistors, solar cells and other electronic components. It is capable of printing large areas and can create variety of substrates making it suitable for next generation electronics. Inkjet printing with graphene is extremely promising, but it is a tedious task because it is difficult to produce an adequate amount of graphene without compromising its electronic properties. Graphene is basic structural element of graphite. Graphite often requires oxidizing conditions that makes the resulting graphene oxide material less conductive than pure carbon. Pure unoxidized graphene can be achieved through exfoliation but the process requires solvents whose residues also decrease conductivity.

![Figure 1: Graphene based ink](Courtesy: The Journal of Physical Chemistry Letters, April 8, 2013)

**Cable type lithium ion batteries and flexible LEDs**

In an advancement to flexible lithium ion batteries, LG chem. Ltd demonstrated a new concept of a cable type lithium ion battery for better battery architecture significantly superior to conventional batteries. It resulted in better mechanical flexibility that allowed maximum freedom in designing of a device as the battery could be placed anywhere and take up any shape. Its architecture consists of several electrode (anode) strands coiled to form a hollow spiral core with a multi-helix structure, surrounded by a modified polyethylene terephthalate nonwoven separator membrane. The next layers are aluminium wires and tubular outer electrode (cathode) and finally the cable battery is sealed by a shrunken packaging insulator. The hollow electrode structure favours both electronic and mechanical properties of the battery. The linear shape and Omni-directional flexibility of the cable battery has helped the cell designers in achieving freedom from rigid constraints.

In an addition to this, a bendable inorganic thin film battery has been developed which enables the formation of high temperature annealed electrodes on polymer substrates. The lithium ion battery incorporating the new electrode was integrated with a flexible light emitting diode which demonstrated the feasibility of manufacturing an all in one flexible electronic system. A concern associated with this system is that the flexibility of the battery may mainly arise from the polydimethylsiloxane (PDMS) sheet wrapping and not from the cell components.
Proton Exchange Membrane Fuel Cells

These fuel cells convert chemical energy of the electrochemical reaction between hydrogen and oxygen into electrical energy. It basically consists of an anode, a cathode and an electrolyte membrane separating the anode and cathode. Hydrogen is delivered to the anode and is split into protons and electrons. The protons (H⁺ ions) pass through the electrolyte and reach the cathode. Simultaneously, the electrons reach the cathode after passing through a load and a stream of oxygen is transmitted to the cathode. The oxygen reacts with the protons and electrons reaching the cathode to form water molecules. The formation of water results in a release of energy. The practical efficiency of such a system is approximately 40-60%. However PEMFCs are compact and, therefore, being considered for vehicles and other applications such as mobile phones. It is also being considered for a substitute to alkaline fuel cells in space shuttles.
Supercapacitors
Also called ultracapacitors or double layer capacitor, they are much more effective regenerative energy storage devices than conventional chemical batteries. Unlike regular capacitors, supercapacitors do not have the conventional dielectric. They have a double layer construction with two carbon electrodes immersed in an organic electrolyte. Supercapacitors are very useful in short duration power boost applications. They are already being used to provide backup power for memory in cell phones and microcomputers. They are also being considered as a replacement for batteries in hybrid cars. These supercapacitors are able to discharge on acceleration and charge on braking of a vehicle. Hence, it has several advantages, such as high power density, fast charge and discharge mechanisms, long life cycle, no chemical actions and low impedance. It has limitations like low energy density and availability of power for a short duration only. Research is being undertaken to tackle such limitations.

Figure 4: Double layer capacitor

3. Conclusion
Flexible electronics is at the forefront of technological innovation. We have presented some of the latest devices in this field that are showing a lot of promise. With each passing day, these devices are being improved with the use of nanotechnology. Cable-type Lithium-Ion Batteries, PEMFCs and Supercapacitors are currently being researched and developed. Along with Inkjet printers and Carbon Nanotubes, these devices are already being put into practice. These advancements in technology not only challenge the existing conventional technology but indicate the prospect of completely substituting them in the future.

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